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THE EFFECT OF GAS DENSITY ON THE WORK OF BREATHING IN MAN

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FOREWORD

This work was accomplished in the Biophysics Section, Physiology Branch, under task No. 775802 between January 1964 and February 1965. The report was submitted for publication on 28 December 1965.

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This report has been reviewed and is approved.

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ABSTRACT

The effect of gas density on the work of breathing was studied in 3 normal male subjects. Gas density was varied by decreasing the barometric pressure in an altitude chamber, as well as by varying the percentage of oxygen with nitrogen and helium. Three frequencies of breathing were selected at 8, 16, and 24 breaths per minute to cover the resting physiologic range, with tidal volume adjusted to allow an alveolar ventilation of 6 liters per minute. There appeared to be a slight decrease in the total work of breathing at the lower gas densities, owing to a decrease in the nonelastic work of breathing. The elastic work was not influenced by gas density but did decrease with increasing breathing frequency. The nonelastic work likewise was affected by frequency, decreasing at the lower breathing frequencies. The order of magnitude of these changes, however, would probably not be of any practical significance and thus would not be a factor in the preferential selection of a particular gas mixture–cabin pressure combination for a manned space vehicular environment.

THE EFFECT OF GAS DENSITY ON THE WORK OF BREATHING IN MAN

I. INTRODUCTION

In view of the fact that several different gaseous environments and total pressures are being considered for future long-duration manned space missions, such as the Manned Orbiting Laboratory (MOL), this study was designed to quantitate the rate of the mechanical work of breathing in man in gaseous environments and at barometric pressures contemplated for such a mission to determine whether any significant change in the rate of work would result, owing to a decreased barometric pressure, differences in gas composition, or a combination of both. This information could then be available as a reference for that part of the total energy planning requirements of man necessary for respiratory function and as an additional criterion for gas selection and barometric pressure environment for a manned vehicular system.

Previous researchers have measured the work of breathing in man under conditions of normal atmospheric gas composition and pressure (1-5, 7, 9, 10). One approach to this was to measure the total energy cost of breathing. The increased oxygen composition resulting from hyperventilation was measured (5); by backward extrapolation of the measured data, the cost of resting breathing was estimated. Otis (8) discusses this and similar approaches to measure the work of breathing by an estimation of the total energy cost of breathing. He points out the wide range of values reported by the studies and attributes this variation, in part, to the different methods employed to produce the hyperventilation and to the failure of some investigators to obtain their measurements during a steady state.

A different approach to the measurement of the work of breathing is to estimate the mechanical work done by the breathing muscles (or to substitute a pump for them) by measuring the pressures required to displace a certain tidal volume. Total mechanical work of resting man breathing air at normal barometric pressure was measured by Otis et al. (9) on a voluntarily relaxed normal subject being ventilated in a Drinker respirator. Later, the mechanical work of breathing was measured directly by McIlroy et al. (6), using the intra-esophageal balloon technic. The values reported by the former group on the total mechanical work of breathing were only slightly larger than the values measured by McIlroy et al., who used their technic to measure the work on the lungs alone and the work required to produce air flow, thus implying that the work done on the thoracic cage and abdomen is a small fraction of the total work for ventilation in the resting range. For this reason and because of the ease of recording intra-esophageal pressures, this study was confined to the measurement of the mechanical work done on the lungs alone and the work to produce air flow under conditions of varying gas density, thus neglecting the elastic resistance and the slight viscous resistance which have been shown to exist in the chest wall.

II. MATERIALS AND METHODS

These experiments were designed to measure the elastic and nonelastic mechanical work of the lungs in normal male subjects at rest while breathing gases of different densities and composition. For this, simultaneous dynamic measurements of lung tidal volume and intra-esophageal pressure changes were obtained.

The basic instrument used was a model 350 Servo-Spirometer, which provides volume measurements as an electrical signal. This instrument was especially chosen for these measurements because of the extremely small loading effect on the breathing subjects. A differential pressure transducer monitors the pressure existing in the chamber of the spirometer and compares it with ambient pressure. A pressure deviation as slight as less than a millimeter of water as a result of inspiring or expiring into the spirometer produces an electrical signal from the pressure transducer, which, by means of the servomechanism, results in a pressure null in the spirometer chamber. Thus, the chamber of the spirometer is constantly regulated to ambient pressure, and the respiratory system breathing into the spirometer behaves as if it were breathing to the atmosphere. Volume discrimination of 1 ml. is also available with this spirometer. The regular breathing port of the spirometer was replaced by a specially constructed, large-bore, plastic mouthpiece having a volume of 50 cc., which gradually tapered at its end to allow the subject's mouth to form a comfortable seal. This mouthpiece afforded a minimal dead space and resistance for the system. CO_2 absorber likewise was omitted from the system. The spirometer was calibrated against a Collin's spirometer at ground level and at each experimental altitude prior to the actual measurements. The mechanical system of the spirometer was located inside the altitude chamber, while the amplifier and recorder were located outside. Spirometer temperature was recorded by a mercury thermometer built into the mechanical system.

Specially manufactured rubber balloons were used for measurement of intra-esophageal pressures. The balloons, 15 cm. in length and 1.2 cm. wide, were affixed to a polyethylene catheter of 1.4 mm. I.D. The catheter was connected to a Statham differential pressure transducer ($\pm$ 0.5 p.s.i.) and the balloon swallowed by the subject, after which a volume of 1 cc. of air was introduced into it. The balloon was then positioned in the lower third of the esophagus by advancing the catheter and balloon until a positive pressure was observed, which indicated the entrance of the balloon into the stomach, and then by slowly retrieving the catheter until the most negative pressure was observed, which indicated the exit of the balloon from the stomach and its location in the lower esophagus. This position was permanently fixed for each subject by marking with a small piece of adhesive tape attached to the catheter at the position of the lips. The outputs of both the spirometer and transducer were simultaneously recorded on a model 150 Sanborn 4-channel recorder. The response time of the balloon-transducer complex was found to be less than 0.01 second.

Three normal male adults served as subjects. Several trial experiments were conducted before accumulating data to allow familiarization with procedure and apparatus. There was never evidence of a cold or other respiratory infection in any of the subjects during the actual measurements.

Gas mixtures to be breathed from the spirometer were 100% O_2, 80% N_2–20% O_2, and 80% He–20% O_2, selected in random order, for the ground level (approximately 749 mm. Hg) measurements. At 18,000 feet (380 mm. Hg), the gas mixtures were 100% O_2, 44% O_2–56% N_2, and 44% O_2–56% He; at 27,000 feet (258 mm. Hg), they were 100% O_2, 68% O_2–32% N_2, and 68% O_2–32% He. These mixtures allowed an alveolar oxygen tension at least equal to ground-level equivalents to be maintained at all times, calculated on the basis of the alveolar equation (11). Assumed values of 40 mm. Hg for alveolar carbon dioxide tension and 0.8 for the respiratory exchange ratio were used in this equation.

With the combination of gas composition and decreased barometric pressure reduced to a common denominator, that of relative gas density (20% O_2–80% N_2 at ground level = 1.0), the range of gas densities breathed by each subject was between 0.27 and 1.10 gm./liter STPD (table I).

With the intra-esophageal balloon in position and connected to the pressure transducer, the subject then prebreathed one of the gas mixtures listed above from an aviator's mask and

TABLE I

Absolute and relative gas densities (RGD) of the gas mixtures breathed at each barometric pressure

Gas mixture	Gas density					
	Absolute			Relative		
	Ground level	380 mm. Hg	258 mm. Hg	Ground level	380 mm. Hg	258 mm. Hg
80% N_2–20% O_2	1.30	—	—	1.00	—	—
100% O_2	1.43	0.72	0.49	1.10	0.55	0.38
80% He–20% O_2	0.43	—	—	0.33	—	—
56% N_2–44% O_2	—	0.66	—	—	0.51	—
56% He–44% O_2	—	0.37	—	—	0.28	—
32% N_2–68% O_2	—	—	0.47	—	—	0.36
32% He–68% O_2	—	—	0.35	—	—	0.27

Values are expressed in grams per liter (STPD).

The absolute densities of each mixture are calculated from the percentage of the individual gases that make up the mixture, the latter values being taken from the *Handbook of Chemistry and Physics*, 44th ed., Chemical Rubber Publishing Co., 1963.

Relative gas densities are based on the use of 1.0 for the density of 80% N_2 - 20% O_2 mixture at ground level. The local ground-level barometric pressure averaged 749 mm. Hg.

demand regulator for 3 minutes to effect lung washout. While this was taking place, an attendant flushed the spirometer with the same gas mixture and finally filled the spirometer with this gas to the 7-liter mark. With noseclip in place, the subject was then required to breathe from the spirometer at a frequency of either 8, 16, or 24 breaths per minute. These rates were regulated by following a metronome, and the tidal volume at each of these frequencies was adjusted by spirometer control; i.e., as the subject began the predetermined breathing pattern, his tidal volume was monitored from the recorder tracings by an attendant outside the altitude chamber who was in voice communication with the subject and indicated to him to either increase or decrease the tidal volume until the proper level was attained, which usually occurred within a span of 4 or 5 breaths. The proper matchings of frequencies and tidal volumes afforded an alveolar ventilation of 6 liters per minute at body temperature and pressure, saturated (BTPS), assuming a total dead space of 200 ml., and thereby covered reasonably well the resting physiologic respiratory range. This procedure was repeated so that each of the three gas mixtures was breathed at each of the three frequencies at each of the three barometric pressures. The measurements at ground level were conducted first at least twice on separate days for each subject, followed by measurements at 18,000 feet and 27,000 feet at later dates. The order of breathing frequencies and gases breathed was randomly varied at each of the barometric pressures.

From the simultaneous tracings of tidal volume and intra-esophageal pressure (fig. 1), and after conversion of the tidal volumes from atmospheric temperature and pressure, saturated (ATPS) to body temperature and pressure, saturated (BTPS), the pressure-volume relationships for specific breaths were plotted, thus resulting in a pressure-volume loop (fig. 2). The area resulting from the loop was then integrated by planimetry to give the work involved for individual breaths.

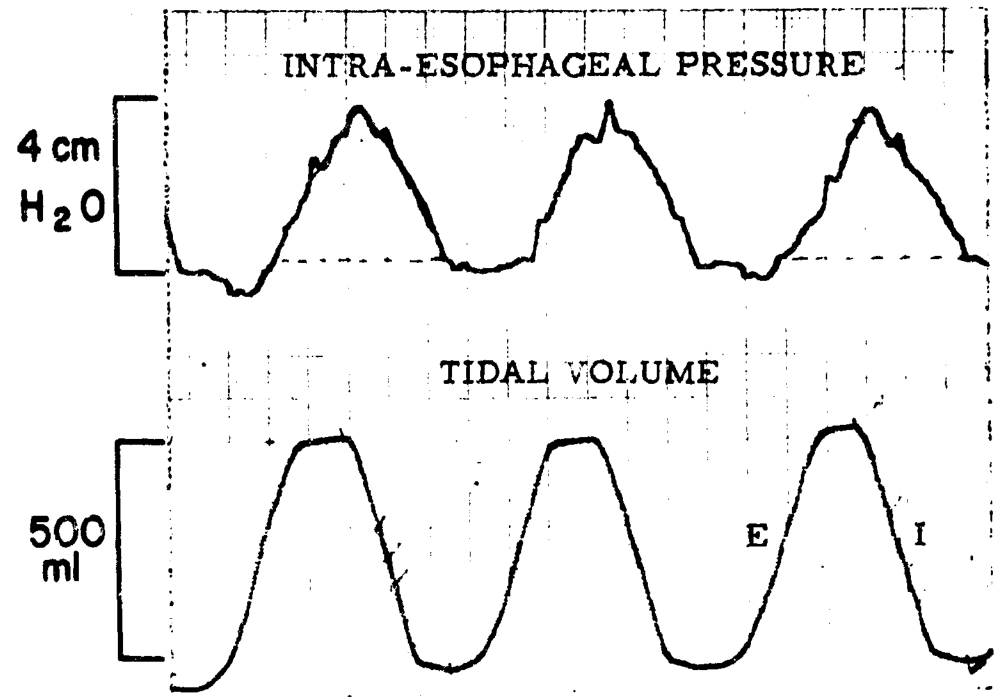

FIGURE 1

Typical simultaneous tracing of intra-esophageal pressure and tidal volume while breathing 100% O_2 at ground level at a frequency of 16 breaths per minute. I *and* E *represent the inspiratory and expiratory phases, respectively.*

The area *OIAB* in figure 2 represents the total work required by the lungs on inspiration. The area *OAB* represents the work done against the elastic forces on inspiration, and the area *OIA*, the work done against nonelastic forces on inspiration—i.e., to overcome tissue friction and to produce air flow in the airway. As shown by this diagram and as actually observed in our measurements, the expiratory portion of the loop, *OAE*, which represents the work necessary to overcome the nonelastic resistance to expiration, is enclosed within the elastic work area *OAB*, which indicates that expiration is passively performed at the expense of the stored elastic energy. Hence, since the work of expiration as observed under the conditions of this study is "for free," so to speak, only the work of inspiration was considered here.

III. RESULTS

The mechanical work of breathing at frequencies of 8, 16, and 24 breaths per minute under conditions of varied gas composition and barometric pressure was measured in 3 trained, normal subjects. The results are expressed in kilogram-meters per minute and were arrived at by multiplying the work per breath by the appropriate frequency. The work of breathing is broken down into components of elastic work, nonelastic work, and the sum of these—the total work of breathing.

Because the same set of gas compositions was not used for the three altitudes (barometric pressures) studied, each altitude might be considered as a separate experiment. An analysis of variance was computed from the data for each of the three types of work of breathing and each altitude. The analysis provided F-tests for gas composition, frequency, and the interaction of gas composition and frequency. A statistically significant F-test for gas composition would indicate that the average work required for inspiration depends on the gas composition; i.e., the work of breathing varies from one gas composition to another. A statistically significant F-test for frequency would indicate that the work of

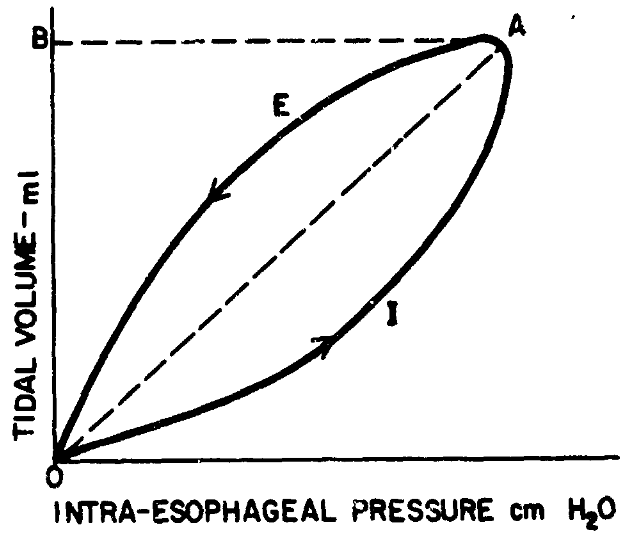

FIGURE 2

A typical pressure-volume loop constructed from a simultaneous tracing (fig. 1) of intra-esophageal pressure and tidal volume of a single breath at ground level while breathing 100% O_2 at a frequency of 16 breaths per minute.

breathing varies from one frequency to another. If the F-test for the interaction between frequency and gas composition were significant, this would indicate that the response pattern to frequency of breathing was different from one gas composition to another.

The individual figures in tables II to V represent the pooled mean values of 4 breaths from each of 3 subjects on two separate experimental days, inasmuch as analysis of variance revealed no significant difference between any of these.

The effect of gas composition on either the total work, elastic work, or nonelastic work at any of the three barometric pressures was statistically insignificant except in the case of the total work of breathing at ground level (approximately 749 mm. Hg). In this instance, there was significantly less work ($P < .05$) involved in breathing the 20% O_2–80% He mixture as compared to breathing either 20% O_2–80% N_2 or 100% O_2. Examination of the mean values in table II suggests, however, that the differences found are probably not of practical significance. There was no significant difference in the total work of breathing between 20% O_2–80% N_2 and 100 % O_2 at ground level. Also, there was no evidence of an interaction of gas composition and frequency in any case, thus indicating that the response pattern to frequency of breathing was not different from one gas composition to another at any of the three barometric pressures.

Most of the significant differences in the work of breathing were due to the frequency of breathing. The total work of breathing did not vary significantly from one frequency to another at either 380 mm. Hg or 258 mm. Hg, but did vary ($P < .01$) at ground level. As further seen in tables II, III, and IV, the mean values for elastic work tend to decrease as frequency is increased at all three barometric pressures ($P < .005$ at ground level; $P < .05$ at 380 mm. Hg; and $P < .05$ at 258 mm. Hg). On the other hand, the mean values for nonelastic work tend to increase as frequency of breathing is increased ($P < .001$ at ground level; $P < .025$ at 380 mm. Hg; and $P < .05$ at 258 mm. Hg).

Since 100% O_2 was the only gas composition breathed at all three altitudes and at each of the three breathing frequencies, an analysis of variance was computed for this gas for each type of work (table V). These analyses provide a test for the effect of altitude, frequency, and the interaction of altitude and frequency on the three types of work. It is seen that neither altitude nor the interaction of altitude and breathing frequency had a significant effect on either the total, elastic, or nonelastic work of breathing. Frequency showed a significant effect on both elastic and nonelastic work, but not on total work; the latter effect is apparently due to the fact that as the elastic work component decreases with increasing frequency and the nonelastic work component increases with increasing frequency, the two seem to carcel each other.

In order to graphically illustrate the effect of gas density per se on the work of breathing and the relationship of the total work of breathing to its component parts of elastic and nonelastic work at each of the three

TABLE II

Effect of gas composition and frequency of breathing on the work of breathing at ground level

	Total work*			
	8†	16	24	
100% O_2	0.254	0.260	0.265	0.260
80% N_2–20% O_2	0.247	0.258	0.289	0.264
80% He–20% O_2	0.236	0.236	0.264	0.245
	0.246	0.251	0.273	
	Elastic work*			
	8†	16	24	
100% O_2	0.192	0.165	0.147	0.168
80% N_2–20% O_2	0.187	0.175	0.173	0.178
80% He–20% O_2	0.186	0.162	0.162	0.170
	0.188	0.167	0.161	
	Nonelastic work*			
	8†	16	24	
100% O_2	0.0625	0.0952	0.118	0.0918
80% N_2–20% O_2	0.0593	0.0831	0.116	0.0860
80% He–20% O_2	0.0498	0.0737	0.102	0.0751
	0.0572	0.0840	0.112	

*Work is expressed in kilogram-meters per minute.

†Breaths per minute.

TABLE III

Effect of gas composition and frequency of breathing on the work of breathing at 380 mm. Hg

	Total work*			
	8†	16	24	
100% O_2	0.231	0.216	0.222	0.223
56% N_2–44% O_2	0.222	0.239	0.241	0.234
56% He–44% O_2	0.213	0.209	0.215	0.212
	0.222	0.221	0.226	
	Elastic work*			
	8†	16	24	
100% O_2	0.176	0.155	0.141	0.157
56% N_2–44% O_2	0.185	0.168	0.149	0.167
56% He–44% O_2	0.179	0.145	0.137	0.154
	0.180	0.156	0.142	
	Nonelastic work*			
	8†	16	24	
100% O_2	0.0550	0.0606	0.0810	0.0656
56% N_2–44% O_2	0.0370	0.0711	0.0914	0.0665
56% He–44% O_2	0.0340	0.0640	0.0778	0.0586
	0.0420	0.0652	0.0834	

*Work is expressed in kilogram-meters per minute.

†Breaths per minute.

breathing frequencies, the data on work of breathing previously presented in tables II to V are plotted in figure 3 in terms of relative gas density—i.e., the combination of a particular gas composition at a particular barometric pressure. The gas densities are relative to the use of 1.0 for the density of 20% O_2–80% N_2 mixture at ground level and were calculated as described in table I. Figure 3 illustrates that with decreasing gas density at each frequency of breathing, there is a tendency for the total work of breathing to decrease. This tendency, although slight and in part paradoxical at the extreme lower gas densities, is apparently a result of the concomitant slight decrease in nonelastic work with decreasing gas density and is not due to any change in elastic work, which intuitively would not be expected to be affected by a change in gas density. It also appears from the plot that at any particular gas density, the total work of breathing is only slightly greater at a frequency of 24 breaths per minute. On the other hand, there is an apparent real effect of frequency on the elastic and nonelastic work of breathing, with the elastic work greater at the lower frequencies and the nonelastic work greater at the higher frequencies.

McIlroy et al. (6), using the esophageal balloon technic to measure the mechanical work of respiration in normal resting subjects breathing air at normal atmospheric pressure, reported values between 0.19 and 0.46 kgm./min. with a mean of 0.29 kgm./min. These values represent the total work of breathing. Of this, 69% of the work expended is exerted against the elastic resistance of the lungs and

TABLE IV

Effect of gas composition and frequency of breathing on the work of breathing at 258 mm. Hg

	Total work*			
	8†	16	24	
100% O_2	0.208	0.224	0.239	0.223
32% N_2–68% O_2	0.220	0.231	0.251	0.234
32% He–68% O_2	0.214	0.244	0.255	0.238
	0.214	0.233	0.248	
	Elastic work*			
	8†	16	24	
100% O_2	0.171	0.157	0.147	0.158
32% N_2–68% O_2	0.178	0.159	0.155	0.164
32% He–68% O_2	0.178	0.161	0.154	0.165
	0.176	0.159	0.152	
	Nonelastic work*			
	8†	16	24	
100% O_2	0.366	0.0665	0.0919	0.0650
32% N_2–68% O_2	0.0426	0.0719	0.0966	0.0704
32% He–68% O_2	0.0363	0.0822	0.101	0.0732
	0.0385	0.0735	0.0965	

*Work is expressed in kilogram-meters per minute.

†Breaths per minute.

the remainder is exerted for the nonelastic work of breathing. Assuming that the breathing rate of their resting subjects was approximately 16 breaths per minute, we find our values for subjects breathing air (20% O_2–80% N_2) at ground level at this rate (table II), and as indicated by the mean values at a relative gas density of 1.0 in figure 3, compare almost identically to theirs; that is, the mean value for the total work of breathing is 0.258 kgm./min. in our measurements and for the elastic work is 0.175 kgm./min., or 68% of the total work, with the remainder for the nonelastic work of breathing.

At a frequency of 8 and 24 breaths per minute and again based on the values in figure 3, the elastic work of breathing comprises 76% and 41%, respectively, of the total work of breathing. This finding corresponds to expectations, since at the lower frequencies larger tidal volumes are required to effect the fixed alveolar ventilation of 6 liters per minute and thus a greater proportion of the total work would be required to overcome lung elasticity.

IV. DISCUSSION

In only one case did there appear a statistically different effect on any of the three components of the work of breathing which was due to gas composition alone. This was in the case of total work at ground level, where there was significantly less work ($P < .05$) required to breathe the 20% O_2–80% He mixture than either 20% O_2–80% N_2 or 100% O_2. The absolute values of these differences as shown in table II, however, indicate that this is probably not of practical significance. Since the greatest difference in gas densities was between those gases breathed at ground level (i.e., relative gas density of 20% O_2–80% N_2 = 1.0; 20% O_2–80% He = 0.33; and 100% O_2 = 1.10), any differences in the total work of breathing due to gas density would have been expected to show up in this instance. At 380 mm. Hg and at 258 mm. Hg there was no significant difference in the total work of breathing between the three gas mixtures breathed, which is attributable to the relatively small differences in the gas densities at each of these two altitudes. This latter fact was due mainly to the increasing percentage of oxygen that was added to each mixture with increasing altitude in order to maintain an alveolar oxygen tension equivalent to normal ground-level values.

At all three barometric pressures, the influence of frequency on the nonelastic work of breathing—i.e., the work required to move the gases in the airway—was evident. As the frequency of breathing a particular gas mixture at each barometric pressure increased from 8 to 16 to 24 breaths per minute, a concomitant increase in the work rate was required to move the gases in the airway in response to the increased flow rate. The effect of frequency on the elastic work of breathing also confirmed expectations; i.e., the elastic

TABLE V

Analysis of variance on data for work of breathing 100% O_2 at different altitudes and breathing frequencies

	Work	Altitude	Frequency	Altitude-frequency
100% O_2	Total	N.S.	N.S.	N.S.
	Elastic	N.S.	$< .025$	N.S.
	Nonelastic	N.S.	$< .025$	N.S.

Total work*

	8†	16	24	
Ground level	0.254	0.260	0.265	0.260
380 mm. Hg	0.231	0.216	0.222	0.223
258 mm. Hg	0.208	0.223	0.239	0.223
	0.231	0.233	0.242	

Elastic work*

	8†	16	24	
Ground level	0.192	0.165	0.147	0.168
380 mm. Hg	0.176	0.155	0.141	0.157
258 mm. Hg	0.171	0.157	0.147	0.158
	0.180	0.159	0.145	

Nonelastic work*

	8†	16	24	
Ground level	0.0625	0.0952	0.118	0.0918
380 mm. Hg	0.0550	0.0606	0.0810	0.0656
258 mm. Hg	0.0366	0.0665	0.0919	0.0650
	0.0514	0.0741	0.0969	

*Work is expressed in kilogram-meters per minute.

†Breaths per minute.

work of breathing decreased as the frequency of breathing was increased, since at the higher frequencies where the tidal volumes were smaller for the fixed alveolar ventilation of 6 liters per minute, less work was required to overcome the elastic recoil of the lungs during inspiration. The elastic work of breathing was not influenced significantly, however, by differences either in gas composition or in barometric pressure, as would be expected intuitively.

By reducing the variables of gas composition and barometric pressure to a single parameter of relative gas density, the effect of gas density per se on the total, elastic, and nonelastic work at each of the three breathing frequencies is shown in figure 3. At each frequency there appears, in general, a slight decrease in the total work of breathing with decreasing gas density. This tendency for a decrease in total work of breathing with decreasing gas density is obviously a result of the slight decrease in the nonelastic work component of breathing as gas density decreases. The tendency for the nonelastic work of breathing to be less with decreasing gas density is probably due to not only the greater ease of moving a less dense medium in the airway, but also the fact that there would be less tendency for turbulence to occur with decreasing gas density. This fact is based on the relationship

$$R = \frac{VDP}{n}$$

where R is Reynolds number (i.e., the tendency to turbulence), V is the linear velocity of the gas in the airway, D is the diameter of the airway, P is gas density, and n is gas viscosity. The less the turbulence, the less would be the work required to move a given volume of air, since the efficiency of the system would be greater. Differences in viscosity between the various gases breathed were relatively small, with the greatest difference being between the 20% O_2–80% N_2 mixture (0.171 millipoise, STPD) and both 100% O_2 and the 68% O_2–32% He mixture (0.188 millipoise, STPD), the mixture values calculated theoretically from the percentage of the individual gases that make up the mixture, the latter values being taken from the reference mentioned in table I. The viscosities between all the gas mixtures breathed were similar because of inherent similarity in the gases themselves and because gas viscosity is unaffected by changes in barometric pressure, according to Maxwell's law. Thus, the nonelastic work of breathing would not be expected to be influenced by viscosity under the conditions of this study.

The overall tendency for the nonelastic work of breathing to decrease with decreasing

gas density is probably not of any practical significance, not only because of the very slight absolute magnitude of change, but especially since the elastic work of breathing a priori is approximately two-thirds of the total work requirement and, as shown in figure 3, the elastic work is independent of gas density under these conditions.

The effect of frequency on both the elastic and nonelastic work of breathing appears to be more apparent in figure 3. This is only of academic interest, however, since an increase in the elastic work at any particular frequency tends to be cancelled out by a decrease in nonelastic work, with the end result that the total work of breathing at all three frequencies is only slightly and insignificantly different.

By definition, the nonelastic work of breathing is that portion of the total work of breathing required to (a) move the gas in the airway and (b) overcome tissue friction. It seems interesting to note, therefore, that had the trend of decreasing nonelastic work with decreasing gas density been more consistent in linearity, it would be possible then to extrapolate the data of figure 3 to zero gas density. The intercepts for each of the three breathing frequencies thus obtained at zero gas density would then allow an approximation of that portion of the nonelastic work which is independent of providing for gas flow in the airway—i.e. the work required to overcome tissue friction itself during inspiration.

In conclusion, the data indicate that from an operational standpoint, the choice of any one combination of gas composition and altitude over another in this study would be an arbitrary one, based on a consideration of the effect of this combination on the total work of breathing in resting man. This may not necessarily be the case under conditions of greater workloads, such as in exercise or a work situation, and further measurements under these conditions might be worthwhile.

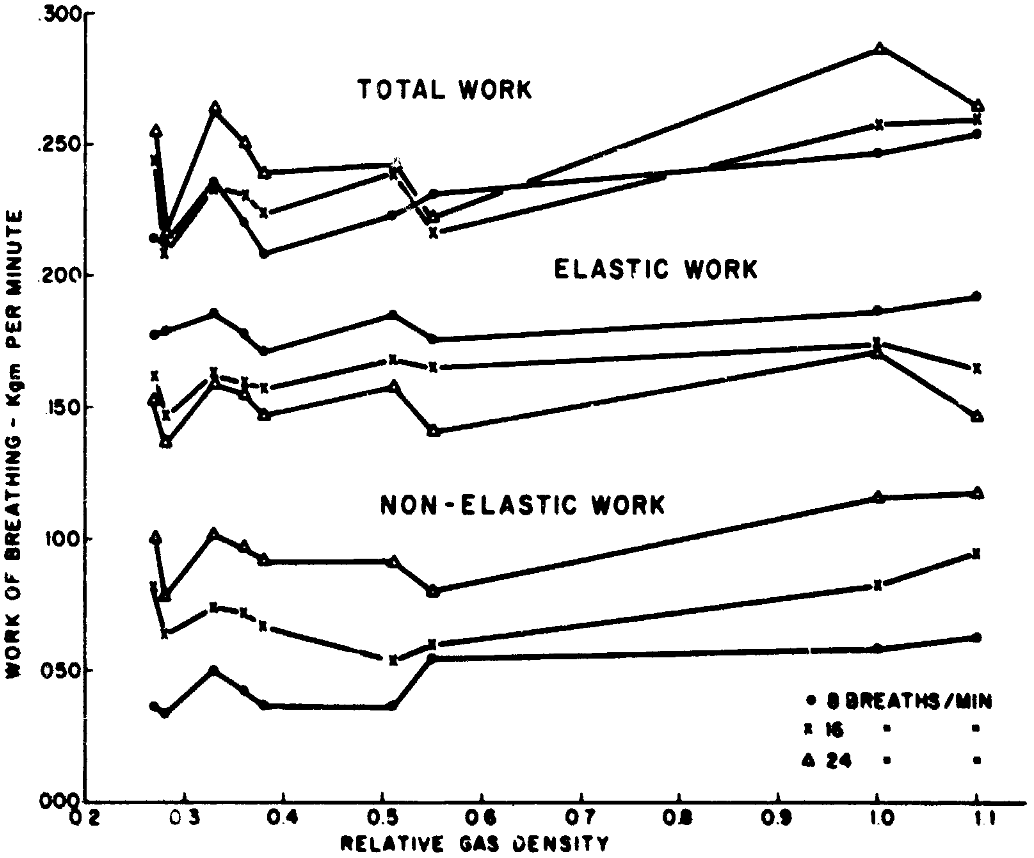

FIGURE 3

The effect of gas density on the total, elastic, and nonelastic work of breathing in man at frequencies of 8, 16, and 24 breaths per minute. Gas densities are relative to the use of 1.0 for the density of 20% O_2–80% N_2 at ground level.

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APPENDIX

TABLE 1A

Effect of gas composition, barometric pressure and breathing frequency on the work of breathing in man

Gas composition	Barometric pressure (mm. Hg)	Rel. gas density*	Total work†			Elastic work			Nonelastic work		
			8‡	16	24	8	16	24	8	16	24
100% O_2	Ground level	1.10	0.254	0.260	0.265	0.192	0.165	0.147	0.0625	0.0952	0.118
80% N_2–20% O_2	Ground level	1.00	0.247	0.258	0.288	0.187	0.175	0.173	0.0593	0.0831	0.116
100% O_2	380	0.55	0.231	0.216	0.222	0.176	0.155	0.141	0.0550	0.0606	0.0810
56% N_2–44% O_2	380	0.51	0.222	0.239	0.241	0.185	0.168	0.149	0.0370	0.0711	0.0914
100% O_2	258	0.38	0.208	0.224	0.239	0.171	0.157	0.147	0.0366	0.0665	0.0919
32% N_2–68% O_2	258	0.36	0.220	0.231	0.251	0.178	0.159	0.155	0.0426	0.0719	0.0966
80% He–20% O_2	Ground level	0.33	0.236	0.236	0.264	0.186	0.162	0.162	0.0498	0.0737	0.102
56% He-44% O_2	380	0.28	0.213	0.209	0.215	0.179	0.145	0.137	0.0340	0.0640	0.0778
32% He–68% O_2	258	0.27	0.214	0.244	0.255	0.178	0.161	0.154	0.0363	0.0822	0.101

*Refer to table I in text for explanation of relative gas density.

†Work is expressed in kilogram-meters per minute.

‡Breaths per minute.

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13 ABSTRACT

The effect of gas density on the work of breathing was studied in 3 normal male subjects. Gas density was varied by decreasing the barometric pressure in an altitude chamber, as well as by varying the percentage of oxygen with nitrogen and helium. Three frequencies of breathing were selected at 8, 16, and 24 breaths per minute to cover the resting physiologic range, with tidal volume adjusted to allow an alveolar ventilation of 6 liters per minute. There appeared to be a slight decrease in the total work of breathing at the lower gas densities, owing to a decrease in the nonelastic work of breathing. The elastic work was not influenced by gas density but did decrease with increasing breathing frequency. The non-elastic work likewise was affected by frequency, decreasing at the lower breathing frequencies. The order of magnitude of these changes, however, would probably not be of any practical significance and thus would not be a factor in the preferential selection of a particular gas mixture - cabin pressure combination for a manned space vehicular environment.

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